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A new model for the growth of faults

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Summary

Conventional fault growth models suggest that faults become larger due to systematic increases in both maximum displacement and length. We propose an alternative growth model where fault lengths are established from an early stage and growth is achieved mainly by increases in cumulative displacement. The model is tested by analysis of fault displacement variations observed in 3D seismic surveys for areas of synsedimentary faulting where sedimentation rates exceed fault displacement rates thereby preserving fault growth histories. The model reconciles the scaling properties of faults and earthquakes and predicts a progressive increase in fault displacement to length ratios as a fault system matures. This growth scheme is most directly applicable to reactivated fault systems in which fault lengths in the cover sequence were inherited from underlying structure and established rapidly; we suggest, however, that the model could also apply to non-reactivated fault systems.

Introduction

Quantitative constraints from ancient fault systems indicate that maximum displacement (D) scales with fault-trace length (L), following the expression:

$$D = cL^n,$$

where c is a constant and n is between 1 and 1.5 (e.g., Walsh and Watterson, 1988; Cowie and Scholz, 1992). The conventional explanation for this relationship is that it represents a growth trend with faults becoming larger due to systematic increases in both maximum displacement and length (Fig.1). Increases in fault length are achieved either by fault propagation or linkage. This growth model has not however been tested using kinematic constraints on faults and questions remain regarding its general applicability.

Established fault growth models predict that the earliest formed faults had lengths that were significantly shorter than their final lengths (Walsh and Watterson, 1988; Cowie and Scholz, 1992). The first earthquake generated for each of these early faults would have had a slip to length ratio described by the earthquake-scaling relationship (e.g., Wells and Coppersmith, 1994). Fault growth is achieved by the superimposition of earthquakes, which increase in size as the fault gets longer. Comparison of fault and earthquake populations suggests, however, that faults have much higher displacement to length ratios than individual earthquakes (Fig. 1), a feature which is at odds with the belief that fault-growth trends define lines of constant displacement to length ratio. Here we present an alternative growth model for faults that is consistent with the existing displacement-dimension data and provides a link between earthquake and fault observations.

Method

In basins where the rate of sedimentation exceeds the fault displacement rate, faults are continually blanketed by sediment throughout their growth. In these circumstances across-fault thickness changes record fault movement histories through time with progressively younger horizons recording less of the growth history. By subtracting the displacements on younger syn-faulting horizons from those of older horizons, referred to as displacement backstripping, we can restore fault displacements to the time of deposition of the younger horizon. Applying this approach we can determine the timing of onset of fault movement along the lengths of individual faults and therefore the amount of lateral fault propagation as the displacement increases (Fig. 2). We have applied this method to normal faults imaged in 3D seismic surveys in the Inner Moray Firth, the Timor Sea, Gulf Coast and South China Sea.

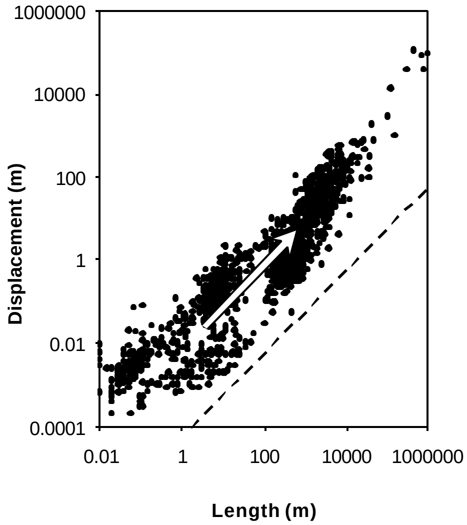

Fig. 1. Published displacement versus length data for normal faults. The arrow illustrates the conventional growth model derived from these data. The bold dashed line is the average position of earthquake data for all types of faults from Wells and Coppersmith (1994).

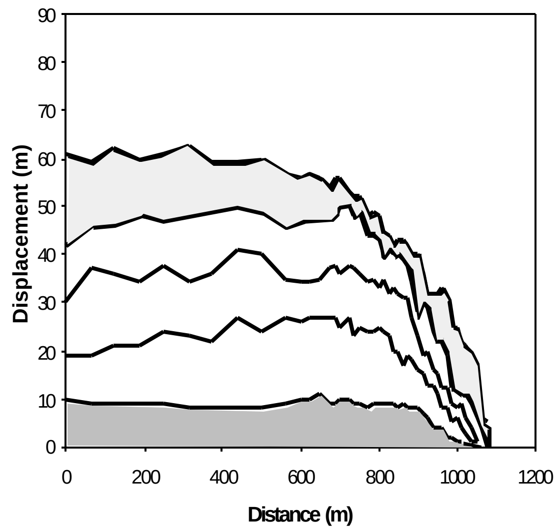

Fig. 2. Profiles of displacement against distance for 5 horizons deposited during the growth of a synsedimentary fault. The highest displacements occur on the oldest horizons. Differences in displacement between successive horizons indicate the displacement which accrued in the time between their deposition. The lateral extent of the first mappable growth interval (coarse stipple) is approximately the same as that for the last interval (fine stipple). The fault therefore did not propagate beyond its initial length as displacement increased

Results

Displacement backstripping of the largest 23 faults in a fault system from the Timor Sea (Fig. 3) demonstrates little or no resolvable fault propagation, i.e. faults had approximately constant lengths following deposition of the oldest syn-faulting horizon (Fig. 4a). Fault growth therefore occured in two distinct phases, an initial phase of rapid fault propagation from the time of initiation of extension to deposition of the oldest mapped synfaulting horizon (1.5myr) followed by a phase in which trace lengths were either constant or decreased through time. It has been previously demonstrated that, within this study area, displacement rates for individual faults are, in general, nearly constant with larger faults having higher rates than smaller faults (Nicol et al., 1997; Meyer et al., in press). Therefore on a plot of displacement versus length, the fault growth curves are parallel to the displacement axis so that displacement to length ratios progressively increased during fault growth (Fig. 4b). Fault length versus elapsed time curves for other areas (Fig. 5) also show that fault propagation occuring predominantly during the initial phase of growth.

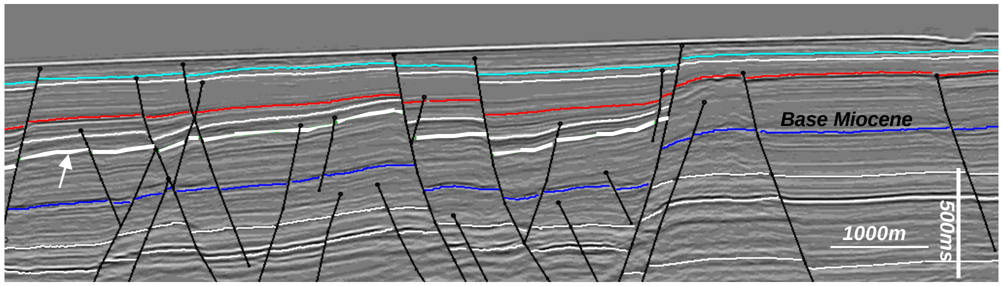

Fig. 3. A seismic section through the Timor Sea dataset. The arrow shows the base of the synrift sequence.

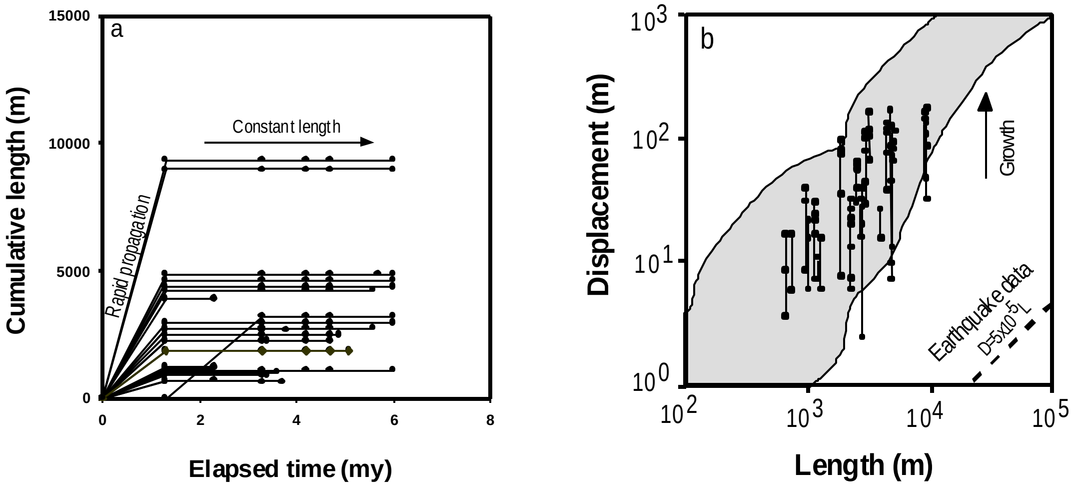

Fig. 4. (a) Growth curves for 23 of the largest faults from the Timor Sea dataset showing changes in fault length with increase in elapsed time from the onset of extension. Faults that became inactive during extension have maximum values of elapsed time <6 my. (b) maximum displacement versus length for the same faults.

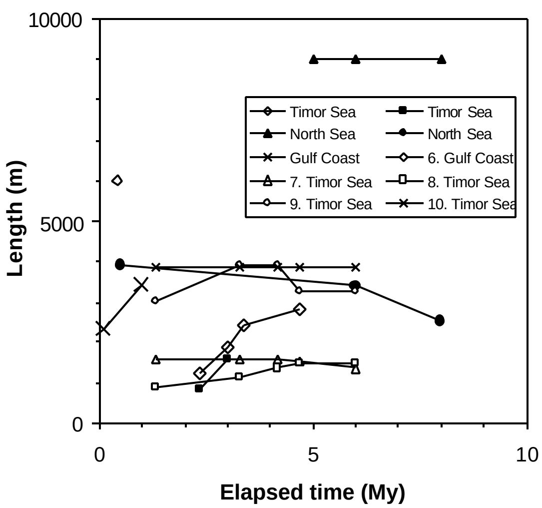

Fig. 5. Growth curves for faults from a variety of areas showing the change in length with increase in elapsed time from the onset of extension. The first growth stage for each fault is not shown but it is assumed that the growth curves pass through the origin. In the majority of cases fault propagation occurs predominantly during this first growth stage.

New model of fault growth

Fault growth histories established from seismic data are not consistent with a model in which faults grow along the trend defined by published displacement versus length data (Fig. 1). Rather the data indicate that faults grow rapidly in length giving displacement to length ratios lower than those for ancient faults and thereafter grow into the data trend by accumulating displacement without significant fault propagation (Fig. 6a). Near-constant fault lengths during subsequent growth are attributed to retardation of lateral propagation by interaction between fault tips (Fig. 6b).

This fault growth model reconciles the very low displacement to length ratios established for earthquakes with the much higher values obtained from ancient faults. If fault lengths are established early with a range of fault lengths lying along the displacement to length trend for earthquakes, these faults can grow in displacement into the field for ancient faults within 20 to 200 earthquake cycles (Fig. 6a). For typical earthquake repeat times (100 to 1,000 years) the initially under-displaced faults grow into the established data trend in 2,000 to 200,000 years; these time intervals are below the resolution achievable from most geological data and are effectively instantaneous.

Many of the Timor Sea faults are reactivated 'basement' faults with lengths inherited from underlying structures. The alternative model of fault growth is a plausible scenario for such reactivated fault systems. Reactivated basement structures are not however a feature of all of the areas studied and there are grounds for suggesting that the model may apply to the growth of non-reactivated fault systems.

Conclusions

Fault histories recorded in thickness changes across synsedimentary normal faults indicate that increase in displacement is often accompanied by little or no fault propagation. These data contradict conventional growth models in which there is progressive growth in fault length and displacement through time. The data are however consistent with a model in which faults grow by an initial phase of rapid propagation followed by accumulation of displacement with subdued fault propagation resulting in a progressive increase in fault displacement to length ratios through time. This alternative model is consistent with the scaling relationships for both earthquakes and ancient faults.

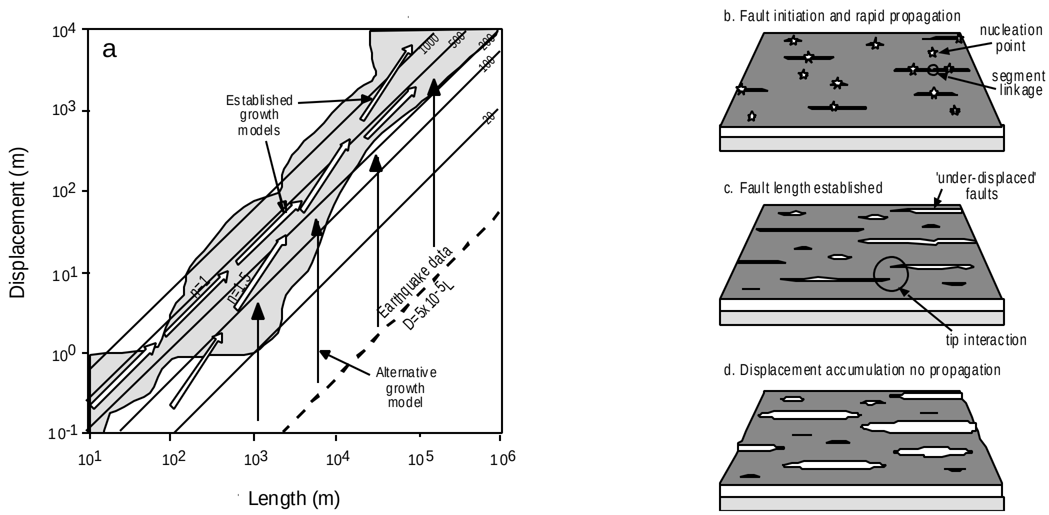

Fig. 6. (a) Log-log plot of maximum displacement vs. length showing growth paths of faults for the established models and our alternative model. Shaded area outlines the field of existing data. The average position of earthquake data for all types of faults from Wells and Coppersmith (1994) is indicated by the thick dashed line. Contours of 20, 100, 200, 500 and 1000 indicate the number of earthquakes required to move cumulative fault displacements along vertical growth trends from the earthquake line. (b-d) Schematic illustration of the proposed fault growth model.

References

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